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学位授与の題目	A Study on the Robust Q-Parametrization Control of Magnetic Bearing Systems（磁気軸受システムのロバストQパラメトリゼーション制御に関する研究）
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学位論文要旨

In this thesis, we utilize the robust Q-Parametrization control theory to design a controller for a magnetic bearing system to stabilize it and solve the problem of imbalance. The robust Q-Parametrization control theory characterize the set of all stabilizing controllers of a given plant in terms of a free parameter Q. The controller Q-parameter is then chosen such that design specifications are achieved. Moreover, other performance and robustness goals are included. The design objectives are formulated as a set of linear equations in the free parameter Q. The free parameter Q is found by simply solving this set of linear equations.

Magnetic bearings are a rather new concept in bearing technology. They take radial loads or thrust loads by utilizing a magnetic field to support the shaft rather than a mechanical force as in fluid film or rolling element.
Magnetic bearings are receiving increased attention nowadays and being used in many industrial, military, and space applications. They are capable of suspending rotating shafts at high speeds without mechanical contact or lubrication, there is no wear. Magnetic bearings have several advantages and disadvantages.

-Advantages

- Very high or low temperature operation
- Low power consumption
- Very long life
- Elimination of oil supply
- Non contamination of working fluid
- Reduction of fire hazard
- Vibration control
- Diagnostic capability

-Disadvantages

- Lower specific load capacity
- Larger bearing
- Higher cost

Magnetic bearings commonly have lower power consumption than rolling element bearings. Also, rolling element bearings have finite life. Because of the non-contact nature of magnetic bearings, they have much longer expected life. Other advantages of magnetic bearings are related to reduced dependence on environmental conditions. Magnetic bearings do not require oil lubrication so they are well suited to applications such as turbomolecular vacuum pumps, turboexpanders, and centrifuges where oil cannot be employed. They can operate at much higher temperatures or at much lower temperatures than oil lubricated bearings.

Intensive studies and research have focused on the control of electromagnetic attractive-force for heavy levitation and suspension applications. Electronically controlled active magnetic bearings offer a number of advantages over the conventional ones:

- ability to control the suspended shaft at any time
- possibility of elimination of vibration by active damping
- ability to adjust the stiffness to produce high position accuracy
- ability to provide for automatic balancing

Imbalance in the rotor mass causes vibration phenomena in rotating machines. Since balancing is rather difficult, there is often a residual imbalance in the rotor. Moreover, the rotor sometimes becomes unbalanced while the machine is in operation. The problems caused by imbalance can be overcome by proper control. In this thesis, in order to solve the unbalance problems, imbalance compensation method and automatic balancing method are proposed for one operating speed. For a number of operating speeds we propose the variable speed control method and gain scheduled control method.

Chapter 2

In this chapter, we show simplified diagram of a 4-axis controlled horizontal shaft magnetic bearings with symmetric structure, and a digital control system for controlling the real experimental magnetic bearing systems.

Chapter 3, 4

In these chapters, we discuss the mathematical modeling. The basic concepts of the flight dynamics is treated in chapter 3, so as to introduce the conventional mathematical model and new mathematical model treating in chapter4.

Chapter 5

This chapter begin with modeling and uncertainty, uncertainty and robustness, coprime factorization, internal stability, robust stability. Then we show euclid's algorithm and the state space representation of the Q-Parametrization controller.

Chapter 6

In this chapter we deal with the simulation results and experimental results to evaluate the levitated states of the magnetic bearing system. And also we show four different approaches so as to make the levitation.

- Q-Parametrization control
  - Evaluation using conventional mathematical model
  - Evaluation using new mathematical model
  - Evaluation using new mathematical model of discrete-time domain
- Evaluation of mixed sensitivity problem control using conventional mathematical model

Chapter 7

In this chapter we deal with two kinds of control methods for the imbalance compensation in the continuous time domain. The first method is to compensate for the unbalance forces by generating electromagnetic forces that cancel these forces (imbalance compensation). The second method is to make the rotor rotates around its axis of inertia (automatic balancing). In this case no imbalance forces will be generated. In imbalance compensation design, the imbalance is represented by sinusoidal disturbance forces, and free parameter Q of the controller is chosen such that rejection of sinusoidal disturbances is achieved. In automatic balancing design, the imbalance in the rotor is assumed as a sinusoidal noise in the measured signal. Namely the sensor measurements should indicate the motion of the principal axis of inertia plus geometrical errors due to the difference between the geometrical axis and the inertial axis.

In this chapter, the controller is designed at speed $p = 0$ (nominal plant) and experimental results are obtained at three different speed $p = 2\pi 17.5$[rad/s], $p = 2\pi 20$[rad/s], $p = 2\pi 22.5$[rad/s] for both imbalance compensation and automatic balancing design. The results show good robustness to model uncertainties and show that the magnetic bearing systems can be used to control vibrations in rotating machinery in two different ways, by compensating for the imbalance forces (imbalance compensation) or by making the rotor rotate around its axis of inertia (automatic balancing).

Chapter 8

In this chapter we propose a imbalance compensation controller design methodology of magnetic bearing system for a certain speed. In order to achieve elimination of unbalance vibration we use the discrete-time Q-parameterization control. And the new mathematical model is utilized. First, we give a new mathematical model for the magnetic bearing in state space form. Second, we explain the proposed discrete-time Q-parameterization controller design methodology for a certain speed of rotation. The controller free parameter Q is assumed to be a proper stable transfer function. Third, we show that the controller free parameter which satisfies the design objectives can be obtained by simply solving a set of linear equations rather than solving a complicated optimization problem. Finally, several simulation and experimental results are obtained to evaluate the proposed controller.

Chapter 9, 10

In these chapters, we propose a controller design methodology using the discrete-time Q-parameterization control for variable speed magnetic bearings and gain-scheduled Q-Parametrization controllers in order to achieve elimination of unbalance vibrations. These chapters are the extension of the controller design methodology developed in chapter 8. We show that the controller free parameter Qwhich satisfies the design objectives can be obtained by simply solving a set of linear equations rather than solving a complicated optimization problem. The operating speeds are $2\pi 10$[rad/sec], $2\pi 20$[rad/sec], $2\pi 30$[rad/sec] for variable speed magnetic bearings and 600[rpm] - 900[rpm] for gain-scheduled controllers. Several simulation results were obtained to evaluate the proposed controller.

Chapter 11

We conclude this thesis in the chapter.

学位論文審査結果の要旨

本学位論文に関し，平成10年1月27日に第1回学位論文審査委員会を開催し，提出された学位論文および関係資料について検討を加え，同2月6日の口頭発表後，審査委員による協議の結果，以下の通り判定した。

磁気軸受は，完全に非接触で物体を回転させることができることから多くの優れた特長をもっており，実用化も進みつつある。磁気軸受に限らない一般的な現象であるが，回転体に不平衡があるとき，その値がわずかであっても高速回転によって振れまわりを生ずる。これを能動制御によって解決するための方法が諸種研究されているが一長一短がある。本論文では，フィードバック制御系の設計をする段階で生ずる自由パラメータQを設定することにおいて，(1) 回転体を慣性中心で回転させる，(2) 幾何学的中心で回転させる，の2つの場合における設計方法を提案している。また，制御システムにロバスト性（頑健性）をもたせ，さらに，回転速度の変化に対しては，ゲインスケジュール法を用いて追随できるよう検討している。実際の4軸制御形磁気軸受実験機について，制御系を設計し，実験を行い所期の結果を得ている。

本論文の成果は，今後磁気軸受の実用化および制御系設計の分野において有益なものであり，高い評価を与えることができる。

以上の内容を総合して本論文は，博士（工学）の学位を受けるに値するものと判定する。